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Using Factor Analysis to Distinguish between Effective and Ineffective Aggregate Stability Indices

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ABSTRACT

Several existing aggregate stability indices are commonly used to represent aggregate stability of soil. Consequently, there is a need to determine how well these common indices characterize or represent aggregate stability. The main objective of this study was to use a multivariate statistical method called factor analysis to determine the effectiveness of eight common indices in measuring aggregate stability. Eighty soil samples (Oxisols and Ultisols) were taken from soil depth of 0-150 mm and from different land uses, such as oil palm, coffee, tea, rubber, pine, fallow, vegetables, and grassland. Aggregate stability of these soils were determined by wet-sieving and water dispersion of the primary particles. Eight aggregate stability indices were used: AIA (average fraction of intact aggregates), WSA >0.3 and >0.5 (water-stable aggregates larger than size 0.3 and 0.5 mm, respectively), MWD (mean weight diameter), CR (clay ratio), WDC (water-dispersible clay), WDCS (water-dispersible clay plus silt), and TP (turbidity percentage). The factor analysis showed that all the aggregate stability indices were related to two common factors, namely, aggregate breakdown resistance and dispersion. By determining how well an aggregate stability index is correlated to either one or both these common factors, the factor analysis ranked the effectiveness of the indices as follows: WSA >0.3 = WDCS > AIA > MWD > WDC > CR. Due to the fact that WSA >0.5 is correlated very strongly with WSA >0.3, both the indices ought to be as effective as the other. The TP index, however, had a questionable efficacy as an aggregate stability index. Based on the findings of this study, it was therefore concluded that only two indices, WSA >0.3 (or WSA >0.5) and WDCS, were sufficient to represent the whole soil aggregate stability.

Keywords: Aggregate stability, factor analysis, Oxisols, structure, Ultisols, wet-sieving

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INTRODUCTION

Soil aggregate stability is the measure of the aggregates resistance to erosion caused by water or wind. There are several indices available to represent a soil's aggregate stability, but it is difficult to determine which index measures or represents aggregate stability better or the best. Currently, the relative effectiveness of several indices is gauged in two approaches.

The first approach is to correlate the aggregate stability indices between one another, as done by Ramos *et al.* (2003), Rohoskova and Valla (2004), and Nichols and Toro (2010). The idea is that if one could find an index that highly correlates with all other indices, it means this potential index is effective because it encompasses many aspects of aggregate stability, or this index can replace many indices. This idea appears sound, but in practice, it may not work. If all the other indices used for comparison are poor measures of aggregate stability themselves, then high correlations between them and the potential index only indicate that this particular potential index is the best among the worst indices. Even if widely accepted or established indices were used for comparisons, the correlations between them and the potential index are expected to be low or moderate, as noted by Epstein (1983). High correlations spell redundancy because the information provided by the potential index about aggregate stability is already provided by others. Low or moderate correlations are inconclusive because there is no way to tell merely from the correlations if the low or moderate correlations are because this potential index has provided information about aggregate stability unaccounted for by the other indices.

The second approach to test the effectiveness of several aggregate stability indices is to correlate them with the soil properties important to aggregate stability. This approach has been used by Albiach *et al.* (2001), Barthes and Roose (2002), Ramos *et al.* (2003), Li *et al.* (2010), and Nichols and Toro (2010). Using simple linear regressions or correlations, effective indices are ones that correlate highly to the soil properties. Again, this idea is sound, but the problem of this particular approach is that although the factors of aggregate stability are many, they may not all affect aggregate stability all the time and in all situations. Numerous researchers have shown that total organic matter may not always influence aggregate stability (Hamblin & Greenland, 1977; Dormaar, 1983; Albiach *et al.*, 2001). The same is also true for iron oxides (Deshpande *et al.*, 1968). Moreover, these factors of aggregate stability can interact with one another; in other words, a factor may not, by itself, have a unique contribution to aggregate stability; instead, it jointly contributes, with another factor or factors, to affect aggregate stability. Such jointly contributions cannot be measured using simple linear regression or by correlations (Lapin, 1993).

The difficulties in determining which index is better or the best can be resolved by studying the proposal by Emerson (1954), and Emerson and Greenland

(1990). They noted that, ultimately, the disruption of aggregates is by two ways, i.e., either by breaking them down into smaller aggregates (slaking), or by discharging their primary particles (dispersion) (*see* Fig.1). As aggregate stability is the measure of the aggregates' resistance to disruption, aggregate stability then encompasses these two subsets, namely, slaking and dispersion.

Whichever measurements of aggregate stability are used, they must ultimately relate back to either or both of the slaking or dispersion phenomena. This insight is crucial because it suggests a way to assess the effectiveness and interrelationship among the various aggregate stability measurements based on how well they relate back to these two aggregate breakdown phenomena.

Fig.2 shows a conceptual model that relates six measurement methods to the two aggregate breakdown phenomena; where y_i is the i-th measurement method; ε_i is the measurement error for the i-th measurement method; η_i is the i-th breakdown phenomenon where $\underline{i}$ = 1 denotes slaking, and i = 2 denotes dispersion; and $\lambda_{1,i}$ and $\lambda_{2,i}$ are the coefficients representing the effect of η_1 (slaking) and η_2 (dispersion), respectively, on y_i. Finally, $\rho_{1,2}$ is the correlation between slaking and dispersion. The model can be described in a linear form by:

$$y_i = \lambda_{1,i}\eta_1 + \varepsilon_i \qquad \text{for } i = 1, 2, \text{ and } 3$$

where these measurements are related to slaking, and

$$y_i = \lambda_{2,i}\eta_2 + \varepsilon_i \qquad \text{for } i = 4, 5, \text{ and } 6$$

for measurements related to dispersion.

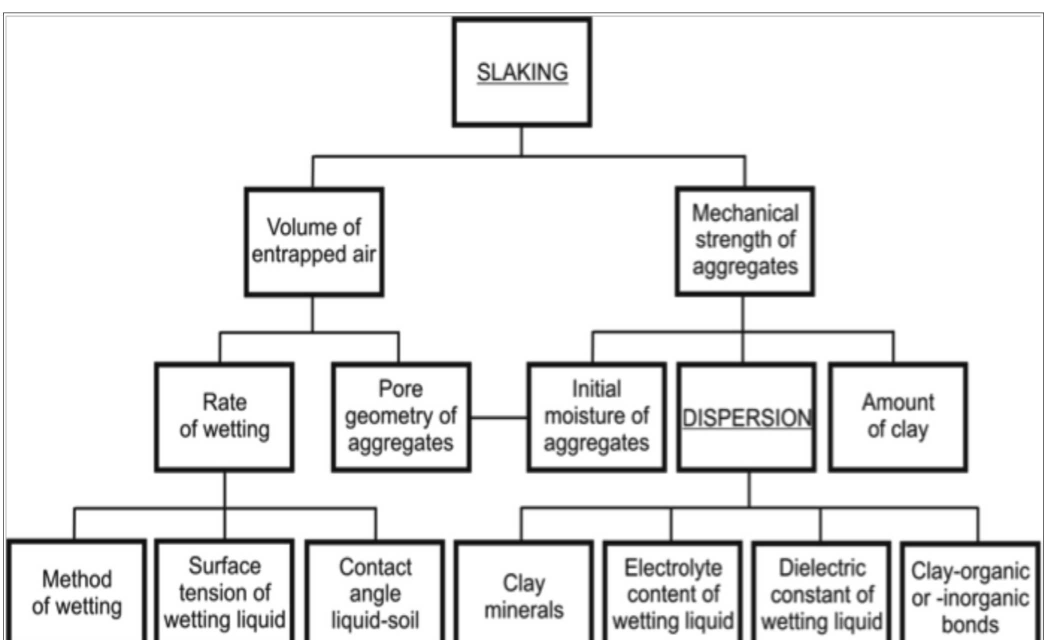

Fig.1: Important factors of slaking and dispersion (after Emerson, 1954)

TABLE 1
The range of the mean particle size distribution for the soils used in this study

Soil taxonomy	Land use	%clay <2 μm	%silt 2-50 μm	%sand >50 μm
Typic Paleudult	Oil palm	8.3 – 34.7	16.7 – 71.4	12.8 – 59.2
Typic Hapludox	Coffee	21.7 – 70.1	7.3 – 29.2	21.6 – 49.1
Typic Paleudult	Fallow	42.3 – 67.7	9.2 – 21.0	22.0 – 36.7
Typic Paleudult	Tea	35.7 – 53.0	15.5 – 17.6	30.5 – 48.5
Typic Paleudult	Vegetables	55.4 – 60.1	5.6 – 7.7	32.7 – 38.1
Xanthic Hapludox	Pine	33.4 – 42.7	19.2 – 21.0	38.6 – 47.0
Typic Paleudult	Rubber	20.7 – 41.6	18.0 – 36.2	22.1 – 61.4
Typic Paleudult	Grassland	43.0 – 51.0	16.0 – 20.6	29.2 – 40.9

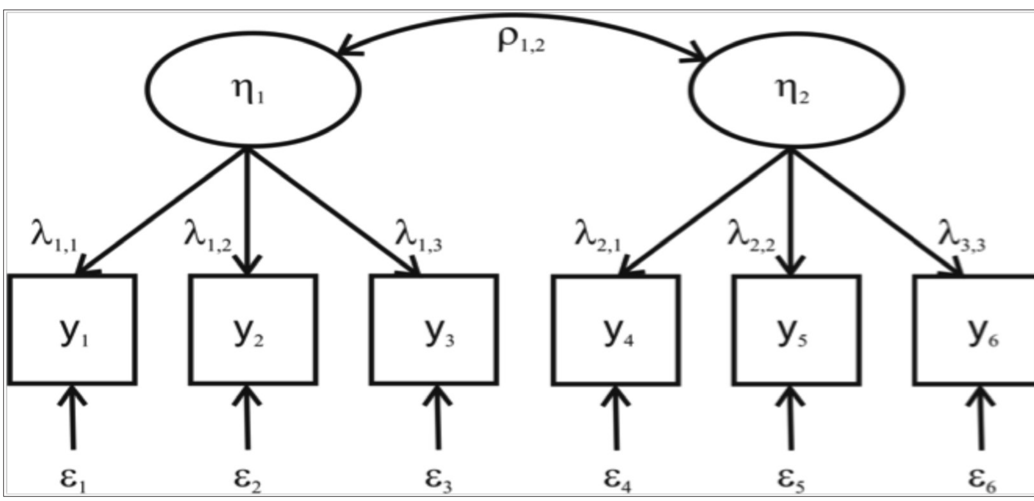

Fig.2: Conceptual model of aggregate stability measurements

Thus, it is possible to determine the effectiveness of each measurement on aggregate stability by determining the value of each λ because its magnitude tells how well a measurement actually measures the real value of aggregate stability. The best measurement is the one with the highest λ for the respective breakdown phenomenon, η. The various values of λ and the correlation between slaking and dispersion can be determined using a multivariate statistical method known as the factor analysis (Brown, 2006). Applied in the context of aggregate stability, the factor analysis will reveal if the various measurements of aggregate stability have two common factors (namely, slaking and dispersion), and the degree each measurement measured slaking and dispersion.

Consequently, the main objective of this study was to use the factor analysis to determine the effectiveness of several established indices as a measure of whole soil aggregate stability.

MATERIALS AND METHODS

Ultisol and Oxisol soils (Table 1) from eight land use areas were sampled from Universiti Putra Malaysia. The land uses included oil palm, coffee, tea, rubber, pine, fallow, vegetables, and grassland. From each land area, ten soil samples were sampled randomly in the field, and the sampling was done from 0-150 mm soil depth using a soil auger. It is important to note that only one soil sample was taken from each sampling point. The soil depth 0-150 mm was selected as the sampling depth because the aggregate stability between the soils is mostly different from one another in the top soil layer compared to the lower or sub-soil layers.

Thus, eighty soil samples were air-dried for at least one week prior to the analysis. The particle size distributions for the soils are shown in Table 1. Before any aggregate stability tests, all the soil samples were pre-wetted by incubation under room temperature and at approximately 98% relative humidity for 24 hours. Meanwhile, the analyses of each soil sample were done in triplicates.

Particle size distribution was analyzed by the pipette method (Gee & Bauder, 1986), and the percentages of the primary particles were used to calculate the clay ratio index (CR) (Bouyoucos, 1935) as follows:

$$CR = \frac{\%\text{sand} + \%\text{silt}}{\%\text{clay}}$$

Wet-sieving was done according to the method proposed by Kemper and Chepil (1965). The samples were dry-sieved using a nest of sieves with openings of 8.0, 5.0, 3.0, 2.0, 1.0, 0.5 and 0.3 mm. Wet-sieving was for 30 minutes, at 40 strokes per minute, and through a vertical distance of 4.0 cm. After wet-sieving, the aggregates retained in each sieve were separately collected, oven-dried, and weighed. After weighing, the sand content in each aggregate size fraction was determined for sand correction calculations. From wet-sieving, four aggregate stability indices were calculated: AIA (average intact aggregates), WSA >0.5 (water-stable aggregates above the size of 0.5 mm), WSA >0.3 (water-stable aggregates above the size 0.3 mm), and MWD (mean weight diameter).

The AIA index (in percent) expresses the average fraction of the aggregates that remained intact (i.e., did not breakdown into smaller pieces) after wet-sieving. It was calculated by:

$$AIA = \frac{100}{N} \times \sum_{i=1}^{N} \frac{W_{a,i} - W_{b,i} - S_i}{W_{a,i} - S_i}$$

where $W_{a,i}$ and $W_{b,i}$ are the weight of aggregates size fraction i before and after wet-sieving, respectively (i = 1 to N), N is the number of aggregate size fractions, and s_i is the weight of sand in aggregate size fraction i. The indices WSA >0.5 and WSA >0.3 (both in percent) were calculated by:

$$WSA > 0.5 = 100 \times \frac{\text{weight of agg.} > 0.5\text{mm} - \text{weight of sand} > 0.5\text{ mm}}{100 - \text{weight of sand} > 0.5\text{ mm}}$$

$$WSA > 0.3 = 100 \times \frac{\text{weight of agg.} > 0.3\text{mm} - \text{weight of sand} > 0.3\text{ mm}}{100 - \text{weight of sand} > 0.3\text{ mm}}$$

where the value 100 in both denominators was the total weight of soil (100 g) used for wet-sieving. The index MWD (mm) expresses a given soil's mean weight diameter after wet-sieving (van Bavel, 1953). It was calculated by:

$$MWD = \sum_{i=1}^{N} \frac{W_{b,i}}{100} \times \bar{x}_i$$

where $\bar{x}_i$ is the mean diameter of the aggregates in the size fraction, *i*; and the value 100 in the denominator, like before, is the total weight of soil (100 g) used for wet-sieving.

Lastly, three more indices, WDC (water-dispersible clay), WDCS (water-dispersible clay plus silt) and TP (turbidity percentage), were used. To calculate WDC and WDCS, the method of Soil Survey Laboratory Staff (1992) was followed. Five grams of uncrushed soil (<2 mm) was added into 50 ml distilled water (ratio soil to water was 1:10), and an end-over-end shaking was for 30 minutes and at 40 rpm. The contents were then poured into a 1-liter measuring cylinder; the volume made up to one litre, the solution gently stroked up-down to distribute the contents, and then left for four minutes for the undispersed aggregates and sand particles to settle to the bottom. The clay and silt particles were then siphoned off at 10 cm depth using a 25 ml pipette. At an appropriate settling time, the clay particles were siphoned off at 10 cm depth using a 25 ml pipette. These values were used to calculate the indices WDC and WDCS (both in percentage) as:

$$WDC = 100 \times \frac{\%\text{dispersed clay}}{\%\text{clay (from particle size analysis)}}$$

$$WDCS = 100 \times \frac{\%\text{dispersed clay and silt}}{\%\text{clay and silt (from particle size analysis)}}$$

The index TP (in percentage) was calculated based on the turbidimetric method of Williams *et al.* (1966). Two grams of soil (< 2 mm) was added with 20 ml distilled water (1:10) and shaken end-over-end for 30 minutes and at 40 rpm. Another 2 g of the same soil sample (< 2 mm) was added with 20 ml Calgon (sodium hexametaphosphate) and shaken end-over-end for 15-16 hours and at 80 rpm. After shaking, both the solutions were left to settle for 4 minutes, and this was followed by pipetting 1 ml out of each solution. To each of those 1 ml solutions, 24 ml of distilled water was added, mixed, and their turbidities were immediately read using a turbidity meter (ELE Paqualab, ELE International, Hertfordshire, England). The TP index was calculated by

$$TP = 100 \times \frac{\text{turbidity of dispersed sample (in water)}}{\text{turbidity of maximum dispersion (in Calgon)}}$$

The factor analysis was used to identify the structure within the set of aggregate stability indices. Before the factor analysis was used, the data set was tested to determine whether it was appropriate for the factor analysis. For this purpose, two statistical tests of factor analysis appropriateness, Bartlett's (1951) Test of Sphericity and Kaiser-Meyer-Olkin (KMO) measure of

TABLE 2
Correlation matrix between all pairs of the aggregate stability indices

	AIA	MWD	WSA >0.5	WSA >0.3	WDC	WDCS	TP
MWD	0.77**	-					
WSA>0.5	0.91**	0.86**	-				
WSA>0.3	0.87**	0.80**	0.98**	-			
WDC	-0.45**	0.26*	-0.45**	-0.47**	-		
WDCS	-0.63**	-.041**	-0.66**	-0.69**	0.77**	-	
TP	0.15	0.23*	0.34**	0.43**	-0.10	-0.10	-
CR	-0.63**	-0.61**	-0.77**	-.076**	0.37**	0.53**	-0.34**

* $p < 0.05$; ** $p < 0.01$

sampling adequacy, were used (Tobias & Carlson, 1969). The factors were extracted by Principal factor extraction method, while the number of factors was selected based upon Cattell's Scree test, and the rotation of the factors was done using oblique rotation by Direct Oblimin method (Brown, 2006). All the factor analysis computations were done using SPSS for Windows version 16 (SPSS Inc., Chicago).

RESULTS

The interrelationships between the eight aggregate stability indices were determined using the factor analysis. However, before any analysis, the indices were checked for violations of normality. Only the clay ratio (CR) index showed violation of normality (skewness=2.71; kurtosis=7.79), and was transformed by ln(CR×100).

All indices generally showed moderate to strong correlations with one another (Table 2). Meanwhile, WSA >0.5 was found to strongly correlate with WSA >0.3 (r=0.98**). In addition, both of these indices generally correlated the highest with all the other indices. The correlation between each of these indices with MWD was strong (r=0.86** for WSA >0.5 and r=0.80** for WSA >0.3); however, this was not as strong as AIA (r=0.91** for WSA >0.5 and r=0.87** for WSA >0.3). Compared with MWD, the AIA index had stronger correlations with the other indices.

Based on the strength of the correlation coefficients, there were generally three groups of indices. The first group comprised the AIA, MWD, WSA>0.5, and WSA >0.3 indices. These indices had stronger correlations between themselves than their correlations with the indices in the second group of indices: WDC, WDCS, and CR. The indices in the second group, however, correlated only moderately between themselves.

The third group of indices actually comprised of only a single index, i.e. TP. This sole index correlated poorly with almost all of the other indices. Nonetheless, TP correlated positively with the indices in the first group (AIA, MWD, WSA >0.5,

TABLE 3
Principal component transformation to determine the relationship between the TP index with the rest of the other indices

Indices	Component 1	Component 2	Component 3
WSA >0.3	**0.94**	-0.59	-0.43
AIA	**0.92**	-0.54	-0.13
MWD_W	**0.91**	-0.28	-0.21
CR	-0.80	0.46	0.43
WDC	-0.36	**0.95**	0.12
WDCS	-0.59	**0.93**	0.12
TP	0.27	-0.11	**-0.99**

and WSA >0.3), but negatively with the indices in the second group (CR, WDC, and WDCS).

The method by Flury and Riedwyl (1988) was followed to determine if TP possessed a questionable efficacy as an aggregate stability index. The principal component analysis, a variant of the factor analysis, was used to explain as much variance among the indices as possible, i.e. to represent the relationship patterns in the correlation matrix to fewer components so that the interrelationships among the indices could become clearer. For the subsequent analyses, WSA >0.5 was disregarded as it could be represented by WSA >0.3 because of their high, almost perfect, correlation between each other. Three components were extracted based upon the Scree test and rotation was by the Direct Oblimin method.

Table 3 shows the results of the principal component transformation (component extraction and rotation) of the indices. It shows that TP revealed a questionable efficacy as an aggregate stability index. In fact, TP almost entirely defined the third component. It highly correlated with the third component (r=-0.99), whereas, the other indices insignificantly correlated with the same third component. The first and second components moderately to strongly correlated with all the indices, except with TP. Moreover, the correlation matrix between the third component and the indices (*see* Table 3) resembled the correlation matrix between TP and each of the other indices, as previously shown in Table 2. Thus, TP appeared to be the third component itself, i.e. a separate "entity" from the rest, representing a different concept other than aggregate stability. In a preliminary analysis, including TP into the factor analysis was found to have reduced the reliability of the factor analysis model. For example, including the TP index into the factor analysis was shown to reduce the KMO sampling adequacy and the total variance accounted for by the factor model. Therefore, the TP index was discarded from the subsequent analyses.

As for the factor analysis, the following six indices were used: AIA, MWD, WSA >0.3, WDC, WDCS, and CR. Prior to the analysis, all the indices were standardized to

TABLE 4
Correlation of the common factors with the aggregate stability indices; (a) unrotated factor structure, and (b) rotated factor structure

(a) unrotated factor structure

Indices	Factor 1	Factor 2	Variance explained by the factors
WSA >0.3	0.96	0.19	0.97
AIA	0.88	0.17	0.80
WDCS	-0.82	0.54	0.97
MWD	0.77	0.41	0.76
CR	-0.73	-0.14	0.55
WDC	-0.60	0.51	0.62
Variance explained by the indices	0.64	0.13	0.78

(b) rotated factor structure

Indices	Factor 1	Factor 2
WSA >0.3	**0.98**	-0.63
AIA	**0.89**	-0.57
MWD	**0.86**	-0.34
CR	**-0.74**	0.48
WDCS	-0.61	**0.98**
WDC	-0.42	**0.79**

have zero means and variances of one. The appropriateness of the data was tested and found to be suitable for the factor analysis because of the following: (1) Bartlett's Test of Sphericity was convincingly rejected (389.99; $p<0.0001$), and (2) KMO sampling adequacy was measured at 0.8 (1.0 being the highest). At this KMO measure, the appropriateness of the data for the factor analysis was rated as "meritorious", i.e. one rank lower than the highest rating (Kaiser & Rice, 1974). Moreover, the factor analysis produced a low anti-image covariance matrix and reproduced the correlation matrix (as shown in Table 2) accurately with no residuals having absolute values above 0.05. These validation results indicated that using the factor analysis was appropriate to determine the internal structure of these six indices. Extraction of factors was done through the Principal factor method, while rotation was by the Direct Oblimin method. Two common factors were selected based on the Scree test. The results gathered from the factor analysis are shown in Table 4.

The data presented in Table 4 show that the six aggregate stability indices, though different from one another, were related to one another by two common factors. In other words, the six indices were ultimately related to two general aspects of aggregate stability—as represented by the two common factors.

To identify the first and second common factors, it is important to consider the proposal by Emerson (1954), as well as Emerson and Greenland (1990), shown in Fig.1. As mentioned previously, the researchers noted that the aggregate breakdown encompasses only two main phenomena, namely, slaking and dispersion. Slaking is the breakdown of the aggregates due to explosion of entrapped air within the aggregates, whereas, dispersion is the discharge of the primary particles from the aggregates. It is crucial to highlight that slaking is usually measured using the wet-sieving method.

From the factor structure in Table 4b, the first common factor correlated strongly with the first three indices; namely, AIA, MWD, and WSA >0.3. These three indices are so-called the "wet-sieving indices" because they were derived from the results of the wet-sieving process. In addition, the three indices tended to measure the ability of the aggregates to retain their sizes during the disruptive effects of water. On the other hand, the second common factor correlated more strongly with the "dispersibility indices" that were derived from the dispersion of clay and silt particles. These indices were WDC and WDCS.

Based on the proposal by Emerson (1954), and Emerson and Greenland (1990), the first common factor could therefore be interpreted as slaking, while the second common factor as dispersibility. Although the first common factor correctly represents slaking, it is an imprecise description of how aggregates breakdown. Slaking is only one way larger aggregates could breakdown into smaller pieces. Other physical disruptions, such as by water agitation during wet-sieving or the falling impacts of raindrops, can also cause aggregate breakdown. Therefore, it would be more precise to interpret the first common factor as representing a larger, more generic aspect than slaking. Thus, the first common factor was interpreted as representing the aggregate breakdown resistance, while the second common factor remained as the dispersion aspect.

While the data in Table 4b helped to identify the two common factors, those in Table 4a were used to determine the effectiveness of the indices. The main criterion to determine the effectiveness of an index is to determine the proportion of its variance involved in the measurement of aggregate stability. The data in Table 4a revealed that WSA >0.3 and WDCS were the two most effective indices of aggregate stability. This was because 97% of the variance in WSA >0.3 and in WDCS could respectively be explained by the two common factors; that is, only a mere 3% of their variance was not involved in the measurement of aggregate stability. The least effective index was CR because only about half of its variance could be explained by the two common factors. Thus, the effectiveness of indices could be ranked as follows: WSA>0.3 = WDCS > AIA > MWD > WDC > CR.

Although WSA >0.3 and WDCS were equally the most effective indices, their measurement emphasis on aggregate stability was different from each other. WSA

>0.3 measured the aggregate breakdown resistance very strongly (r=0.96) but almost not measuring dispersion at all (r=0.19). WDCS, on the other hand, measured both aggregate breakdown resistance (r=-0.82) and dispersion (r=0.54). For aggregate breakdown resistance, WSA >0.3 not only measured this aspect more effectively than WDCS, it this was also done more effectively than any other indices. For dispersion, however, WDCS clearly measured the second aspect of aggregate stability more effectively than WSA >0.3, as well as measuring dispersion the highest as compared to the other indices. Tables 4a and b show that no index measures aggregate breakdown resistance and dispersibility equally well.

This also means that to measure aggregate stability more effectively, only two indices (WSA >0.3 and WDCS) are sufficient. In this way, both the aspects of aggregate stability would be measured: WSA >0.3 stressing very strongly on the aggregate breakdown resistance aspect, and WDCS index is needed to include or measure the dispersion aspect.

The factor model could explain 78% of the variance in all the six indices (*see* Table 4a). All the six indices could explain 64% of the variance in the aggregate breakdown resistance. In addition, 13% of the variance in dispersibility was explained by all six indices. This imbalanced proportion indicated that the six indices measured the breakdown resistance of the aggregates more than dispersibility. This is true for every index.

Finally, the factor analysis showed that the correlation coefficient between the two common factors was -0.55, suggesting that the aggregate breakdown resistance and dispersion shared a moderate and inverse relationship with each other, and both shared approximately 30% of the variance.

DISCUSSION

The factor analysis has showed that no matter how different the aggregate stability indices are from each another, or what aspects of aggregate stability they measure or emphasize, all the indices have been found to ultimately relate to either or both of the aggregate stability phenomena; aggregate breakdown resistance and dispersibility. These phenomena were slightly modified from what Emerson (1954) and Emerson and Greenland (1990) had earlier proposed (Fig.1). The researchers further remark that aggregate stability encompasses two main aspects, namely, slaking and dispersion. However, to narrow the first main aspect of aggregate stability to slaking is imprecise. This is because, aggregates can also breakdown into smaller aggregates by the destructive forces from water agitation or the falling impact of raindrops, apart from slaking. Therefore, it would be more precise to represent the first aggregate stability aspect as aggregate breakdown resistance rather than merely slaking.

Thus, the factor analysis provides a way to distinguish effective indices, which include those that correlate strongly to either one, or both aggregate breakdown resistance and slaking. On the contrary, any index that fails to correlate strongly to at least one of these phenomena has a doubtful efficacy, such as the TP index, as revealed in this study.

In this study, the effectiveness of the six indices could be ranked as follows: WSA >0.3 = WDCS > AIA > MWD > WDC > CR. Due to its strong correlation with WSA >0.3, WSA >0.5 would just be as effective as WSA >0.3. The factor analysis has also been shown to measure aggregate stability effectively on a whole, and only two indices (WSA >0.3, or WSA >0.5 and WDCS) are needed for the purpose. In this way, both the aspects of aggregate stability would be measured: WSA >0.3 (or WSA >0.5), stressing very strongly on the aggregate breakdown resistance aspect, and the WDCS index is needed to include or measure the dispersion aspect. However, if ease and speed of measurement are crucial, WDCS is recommended since it measures aggregate breakdown resistance effectively (although it is not as effective as WSA >0.3 or WSA >0.5), and at the same time, measuring dispersion moderately well. Correspondingly, this kind of dual measuring effectiveness shows that no index measures aggregate breakdown resistance and dispersibility equally well. Thus, an aggregate stability index "specializes" only on one aspect.

The high effectiveness of WSA >0.3 and WSA >0.5 challenges the warning as noted by some researchers that using stability greater than a single size fraction is inaccurate. For example, Low (1954) discovered that the percentage of water-stable aggregates between 0.25 and 1 mm decreased, whilst those greater than 3 mm were found to increase. If a single fraction of aggregates greater than 0.25 mm was used, it would have indicated that aggregate stability did not change. This implies that indices like WSA >0.3 and WSA >0.5 are insensitive to changes in the stability of a given aggregate size fraction. Moreover, using such indices means the researcher tolerates the breakdown of larger aggregates more than the breakdown of smaller aggregates. This is particularly because to pass through a 0.5 mm sieve, for instance, the aggregates in the size 8 mm must breakdown several times or breakdown more than the aggregates of size 1 mm. All the above points are valid but only to some degree, because these points assume that the aggregates from one size fraction behave independently from those in other size fraction. Although the stability of one aggregate size fraction may be different from another, they nevertheless share some soil characteristics that cause various aggregate size fractions to be related (Kemper & Rosenau, 1986; Loveland & Webb, 2003). This means, if the stability of an aggregate size fraction is weak, the stability of other aggregate size fractions would be weak as well. Such close dependencies between the various aggregate size fractions may explain why WSA >0.3 and WSA >0.5 were not affected by the above points.

On the other hand, the commonly used MWD was an ineffective aggregate stability index. Part of the problem is the arbitrary weights assigned to each aggregate size fraction. What MWD actually represents is the weighted average size of the aggregates produced after wet-sieving. The weight assigned to an aggregate size fraction is the average diameter of all the aggregates in that size fraction. However, these weights are arbitrary because there is no proof that, in equal weight, aggregates of 8 mm are always two times more stable than those of 4 mm, even though a specific weight of 8-mm aggregates suggests greater stability than an equal weight of 4-mm aggregates (but this does not necessarily mean two times greater stability). Another problem with MWD is that the various proportions of all the aggregate size fractions are averaged without sand correction. Without such correction, loose or unbounded sand particles are falsely regarded as aggregates. As the soils used in this study are varied widely in their sand amount, sand correction is therefore vital to avoid this fallacy.

The indices AIA and MWD did not measure aggregate stability as well as WSA >0.3 or WDCS, and this is probably because AIA and MWD are the mean values of several proportions. Averaging the various proportions is a crude representation because averaging is sensitive to the distribution of the various proportions. For example, Swift (1991) observed that a single value of MWD used in his study was not the mean aggregate stability of a uniformly grouped normal or Gaussian distribution of aggregate stability values, but it was the mean of widely spaced values with significantly large numbers of values grouped at the extremes of the distribution range. Swift also remarked that using MWD was not suitable, and that it would be better if aggregate stability was observed by comparing the most stable with the least stable aggregates.

Factor analysis also revealed that the indices of aggregate stability tended to emphasize more on the ability of the aggregates to resist breakdown and less on dispersibility. The reason for this is shown in Fig.1. This chart shows that slaking (or aggregate breakdown) is a broader aspect than dispersion, being influenced by more factors, and that dispersion is a subset of slaking. From Fig.1, the factors important to dispersion (such as the characteristics of the liquid and the type of clay minerals) are similar in all the soil types used in this study. Although the soils were not analyzed for their clay mineral types, it is unlikely that these soils (Ultisols and Oxisols) would have such differing clay mineral types to affect dispersibility differently. The only important factor affecting dispersibility differently between the soils is the amount (and type) of organic and inorganic compounds that bind the clay particles (Chenu *et al.*, 2000; Boix-Fayos *et al.*, 2001; Six *et al.*, 2004; Noellemeyer *et al.*, 2008).

Slaking phenomena, on the other hand, is influenced by the same factors affecting dispersion and by other factors unique only to slaking. All this means that slaking is influenced by more extensive factors than dispersion, and why slaking (hence, also aggregate breakdown resistance) tends to be stressed more by the aggregate stability indices as compared to dispersion. In this study, slaking was stressed by the indices approximately five times more than dispersion.

Because dispersion is a subset of slaking, the relationship between the two ought to be at least moderately close. The correlation coefficient between aggregate breakdown resistance and dispersion, as shown by factor analysis, was -0.55, or both factors sharing approximately 30% of variance. This is an expected relationship because the soils that disperse easily ought to breakdown easily as well.

Clay ratio (CR) was shown to be the second worst index of aggregate stability (the worst index was TP). This index CR ignores the level or state of soil structure, and it only takes into account the particle size distribution of the soil. The particle size distribution, though important, would only explain or affect aggregate stability partially; therefore, the correlation of CR to aggregate stability is rather low. As shown in Fig.1, the amount of clay is an important factor not to dispersion but to slaking. This is why, as shown by the factor analysis, CR is correlated more to the first common factor than to the second common factor.

On the other hand, the TP index was the worst and a questionable aggregate stability index. Turbidmetric methods are useful for comparing treatments of the same or similar soils types, but they are unsuitable for comparing the types of soil with different particle size distributions (Douglas & Goss, 1982). In this study, the poor reliability of TP was probably due to two other factors. First, the soils used in this study varied in their colours, ranging from yellow to yellowish brown to brown. These colour variations may have complicated the turbidity comparisons between the soils. Second, in this study, before the turbidities of samples were read, the dispersed soil solutions were diluted 25 times. This was necessary to standardize the soil:water ratio to 1:10 because this particular ratio was also used to measure the dispersibility of the soils, as measured by WDC and WDCS. In keeping to this ratio, however, the turbidities of the dispersed soil solution was too high to be read by the turbidity meter and thus, it had to be further diluted. The error variation caused by these dilutions may have been too large.

The factor analysis is a powerful tool because it determines the internal relationship structure of the various indices. The factor analysis untangles and summarizes the relationship patterns among the indices so that the indices' relationships among each other and to aggregate breakdown resistance and dispersion can be determined.

CONCLUSIONS

The factor analysis has shown that no matter how different the indices are from each other, or which aspects of aggregate stability the indices measure, all the indices are related to two main aspects of aggregate stability, namely, aggregate breakdown resistance and dispersion. By determining how well an aggregate stability index is correlated to either one or both aggregate breakdown resistance and dispersion, the factor analysis ranked the effectiveness of the indices as follows: WSA >0.3 = WDCS > AIA > MWD > WDC > CR. Thus, it could be concluded that only two indices were sufficient to represent the whole soil aggregate stability effectively, namely WSA >0.3 and WDCS.

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